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REVIEW ARTICLE

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A critical review of the state-of-art schemes for under voltage load shedding

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Summary

A blackout is usually the result of increasing load beyond the transmission capacity of the power system. One of the main reasons for power blackouts is voltage collapse. To avoid this problem, the proper corrective measures called load shedding is required. In critical and extreme emergencies, under voltage load shedding (UVLS) is performed as a final remedy to avoid a larger scale voltage collapse. Therefore, UVLS is considered state of the art to achieve voltage stability. This review summarizes and updates the important aspects of UVLS; it also provides principle understanding of UVLS, which are critical in planning such defense schemes. Moreover, this article provides a discussion on recent state-of-art UVLS schemes applied in various power industries. Additionally, the pros and cons of the conventional and computational intelligence techniques are discussed. It is envisioned that this work will serve as one-stop information for power system engineers, designers, and researches.

KEYWORDS

blackouts, power system, under voltage load shedding, voltage collapse, voltage stability

1 | INTRODUCTION

Power blackout refers to the interruption in a power system leading to the absence of power supply in a particular area over a specific period of time.[1,2] Blackouts may lead to multiple power system problems such as highly decreased human productivity, mass litigation, internet breakdown, loss of road and rail traffic control, disruption in air transport services, telephone network collapse, general breakdown in online transactions, restrictions on medical services, and low output from affected companies due to slowed or halted manufacturing process.

The causes of blackouts can be classified as technical or natural. Natural disasters include flood, earthquake (as in the case of the Fukushima Power Plant in Japan),[3] landslide, vehicular accidents or falling off trees on power lines, and

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List of symbols and abbreviations: P-V, active power vs voltage; ANFIS, adaptive neuro-fuzzy interference system; ANN, artificial neural network; BBBC, big bang big crunch; CIT, computational intelligence techniques; FVSI, fast voltage stability index; FA, firefly algorithm; FACTS, flexible alternating current transmission system; FLC, fuzzy logic controller; GAMs, general algebraic modeling system; GA, genetic algorithm; HGAPSO, hybrid genetic algorithm and particle swarm optimization; HPSO-SA, hybrid particle swarm optimization and simulated annealing; LP, linear programming; LSI, line stability index; NN, neural networks; NVSI, new voltage stability index; OLTC, on load tap changer; PSO, particle swarm optimization; PMU, phasor measurement unit; PTSI, power transfer stability index; QIEP, quantum inspired evolutionary programming; Q-V, reactive power vs voltage; SA, simulated annealing; SI, stability index; SCADA, traditional supervisory control and data acquisition; UFLS, under frequency load shedding; ULTC, under load tap changer; UVLS, under voltage load shedding; VCPI, voltage collapse prediction index

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etc. The technical causes include the line faults, stability issues, human errors, faulty equipment, and overloaded lines. Power outages have affected millions of people globally over the last two decades resulting in a major blow to both the economic and social development of societies. Critical infrastructures such as health care facilities, traffic control systems, internet facilities, and other communication systems are examples of the social impact of a power outage.[4-7] Furthermore, the ever-increasing demand without considering the expansion of the transmission system necessitates load shedding to elude a system collapse.

The transition from traditional Supervisory Control and Data Acquisition (SCADA)–based power systems to more intelligent smart grids has picked up the pace in many developed and developing countries. The power system operates near to its stability boundaries, owing to lack of generation or transmission capacity.[8] Under these circumstances, a well-controlled and secured power system whose integrity is in jeopardy needs to shed customer load to recover from an extreme emergency arising from uncontrolled malfunction of the components or the interconnection. Moreover, contingency issues such as faults among others may also lead to cascading failures. These faults may persist for different periods of time as shown in Figure 1.

Instability of voltage is another cause of major power blackouts around the globe.[2,10-13] The major culprit, in this case, is overloaded transmission systems. To solve this problem, it is important to perform load shedding efficiently on an already stressed power system. Reportedly, inadequate load shedding may still result in a blackout. On the other hand, over shedding may create the problem of over frequency and unnecessary customer interruption. However, most of the blackouts in the last couple of decades took place because of voltage instability rather than frequency; therefore, under voltage load shedding (UVLS) is considered a better solution against blackouts.

The occurrence of faults or even a minor effect on the operating characteristics can trigger a series of system failure incidents. Table 1 shows some of the major system failures worldwide.[9]

Both demand and generation depend on frequency and voltage.[14,17-22] The decline in the system frequency and the voltage are due to real and reactive power deficits, respectively.[23] Frequency and voltage must be retained inside satisfactory boundaries to achieve secure and consistent power system operations.[24] Under frequency load shedding (UFLS)[25-29] and under-voltage load shedding (UVLS)[30-35] are generally two well-known methodologies, employed when the frequency or the voltage decreases below a specified edge.

In case of severe faults, such as a sudden decrease in frequency because of generator loss or synchronization loss in interconnected large power systems, UFLS is employed. The application of UFLS is done to arrest, the decline in the frequency of the system by lowering the connected load to match generation capacity with the demand.[25] In fact, UFLS is more effective when electrical islanding occurs; ie, by reducing the load, the frequency is stabilized within the island. Although, UFLS techniques may be employed to prevent blackouts.[36]

UVLS techniques are used to avoid voltage collapse.[9] Furthermore, corrective actions may be needed to resume the system operation within its security margins.[37] UVLS is inherently a "multistep process" as compared with UFLS which is a "one-step process." Note that frequency remains constant throughout the power system, while the voltage at each bus may change depending on the nature of the particular load. Therefore, it is worth mentioning that if a voltage collapse occurs in less than 1 second, or wherever overloads appears without sufficient voltage drop. UVLS becomes unsuitable for these systems or contingencies.[38]

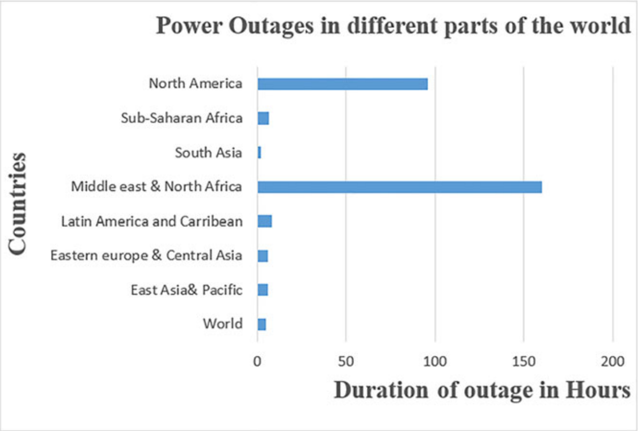

FIGURE 1 Power outages due to faults in different regions of the globe[9]

TABLE 1 Massive power blackouts in the last two decades around the globe

Reference	Country and Year	Hour of Outage, h	Affected People, millions	Reasons
El-Sadek[4]	Egypt, 1990	6	50	Voltage collapse
B. Reports[14]	Brazil, 1999	5	97	Lightning strike
B. Reports[14]	India, 2001	12	226	Transmission line outage
B. Reports; Chang and Wu; and Zhao, Zhang, and He[14-16]	Canada and the Northeast United States	96	55	Human error
Zhao, Zhang, and He[16]	Italy, 2003	18	56	Power lines tripped
B. Reports[14]	Indonesia, 2005	7	100	Failure of transmission line
B. Reports[14]	Brazil and Paraguay, 2009	7	87	Transformers short circuit
B. Reports[14]	Brazil, 2011	16	53	Transmission line defect
B. Reports[14]	India, 2012	15	670	Overloading
Andersson et al and Makarov, Reshetov, Stroev, and Voropai[3,10]	Europe, 2006	2	15	Congestion

UVLS techniques using computer intelligence techniques have gained popularity as a result of their fast convergence time and robustness in large and complex power systems. This review presents a comprehensive outlook of the capabilities, benefits, and drawbacks of the various UVLS schemes used in protecting power systems from blackouts.

Most of the existing literature on a review of UVLS techniques include the following. The basic concepts of UVLS, along with static and dynamic load behaviors is discussed in a previous study.[18] In another study, load characteristics and principles of UVLS are discussed.[35] The authors of an existing study[9] discussed the reasons for the blackout, conventional and computational techniques with their pros and cons. However, this study was limited to only UFLS techniques. UVLS principles and industrial practices are discussed in another study.[39] Merits and demerits of meta-heuristic techniques to solve UVLS problems are presented in a previous study.[40] Another study focused on the application and classification of UVLS schemes including load characteristics.[41]

It is clear from the above discussion that most of the published review work is restricted to some particular domain. According to the author's best knowledge, there is no study that covers all aspects of UVLS in one place. Moreover, the previous review did not cover mathematical load-shedding models and different type of voltage stability indices. The main contribution of this paper is that it provides a comprehensive and detailed discussion of UVLS techniques in a broader range of domains. In particular, this review paper considers the following:

- Fundamentals of UVLS, its applications, and industrial practices.
- Load characteristics along with various approaches to solving the UVLS problem and future trends.
- Discussions on PV and QV curves with respect to contingency conditions.
- Discussion of conventional and computational techniques for solving load-shedding problems along with their pros and cons.
- Load-shedding models based on mathematical equations.
- Different types of voltage and line indices to predict voltage collapse.
- Critical analysis of UVLS schemes based on a genetic algorithm and particle swarm optimization.

The remainder of this paper is organized as follows: Sections 2 and 3 discuss voltage collapse and voltage stability, respectively. Section 4 summarizes the industrial practices and applications. Sections 5 and 6 present UVLS classification and principles, respectively. Section 6 describes the different types of indices used to predict the voltage collapse. Section 7 discusses the various approaches used for load shedding. Section 8 presents a comparison of conventional and computational techniques, and finally, we conclude the paper in Section 9.

Next section explains the phenomena of voltage collapse and voltage stability along with their different categories, which help in finding the collapse point.

2 | VOLTAGE COLLAPSE

Voltage collapse is a severe form of system instability, which could affect many components of the power systems; in fact, it may involve an entire power system voltage collapse that usually occurs when reactive power demand is higher than that of the supply attributed to the lack of reactive power sources. When voltage magnitude decreases very fast with respect to time, a voltage collapse may occur, at that time the voltage magnitude becomes uncontrollable. Voltage collapse incidents mainly depend on transmission system limitations, and it is a sign of voltage instability in the system. Moreover, voltage instability is also attributed to unexpected load increments or a component outage, with the sudden increase in power demand. It is worth noting that most of the existing power systems are reaching maximum transmission capacity efficiency due to increased complexity and loading.[42,43]

Voltage collapse is a major challenge for power system operators.[44-47] Factors such as changing nature loads, dependency on generation remotely positioned away from load centers, and natural load growth increase the risk of voltage collapse.[41,48] The risk of voltage instability further rises because of heavily overburdened power networks and jams during failures and outages. A voltage collapse, in turn, leads to a blackout state.[9,41] Technical and economic viewpoints on UVLS schemes are discussed in another study.[18] If the voltage collapse is expected, UVLS is the most appropriate countermeasure for avoidance.[49-51]

3 | VOLTAGE STABILITY

The load is usually the determinant of voltage instability. Voltage stability describes the capacity of a power system to operate with balanced voltages at all system buses when subjected to a large disturbance with respect to the specified operating conditions.[17] Overloading or involuntary outage of a line or generator typically causes voltage instability, which may lead to increased reactive power demand and eventually resulting in a blackout.[9] Figure 2 shows the stable and unstable operating regions in term of voltage in a power system.

Figure 3 shows the P-V curve used by utility system planners for analysis in obtaining the real power transfer capacity across a transmission interface to supply local load. Once a line trips, the voltage decays faster, which is informative for utility system planners and is termed nose curves.[36] The nature of the load determines the shape of the nose curve at the load center. From the base case, the power and voltage transfer smoothly till the power transfers reach high a level (A3), then the system collapses because of rapid voltage decay causing the interconnected systems to pull out of steps resulting in an increased angle between them. The analysis of P-V curve shows that when a power system operates without contingency (ie, no circuit outage), we observe prolonged nose (curve A nose). On the other hand, if the contingency condition (N-1) arises, its nose point shifts (curve B nose) and the power system is at the risk of collapse. However, if both generator and transmission line failures occur at the same time, ie, worst contingency N-2, a very rapid collapse may arise as its nose appears very early (curve C nose) as compared with the normal operating conditions of the power system.

There are several types of voltage instabilities. The first type is a short term, which occurs in the time frame of seconds; the second type may take few minutes, which is termed as a medium; and finally, the third type of long-term voltage instability whose time periods start from a few minutes to several minutes. Each type of voltage stability is described in further details as follows:

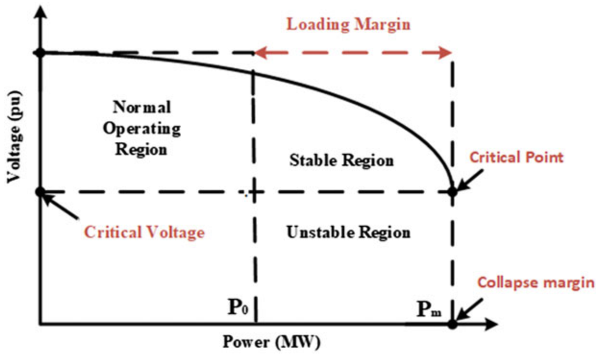

FIGURE 2 Voltage stability margins[42]

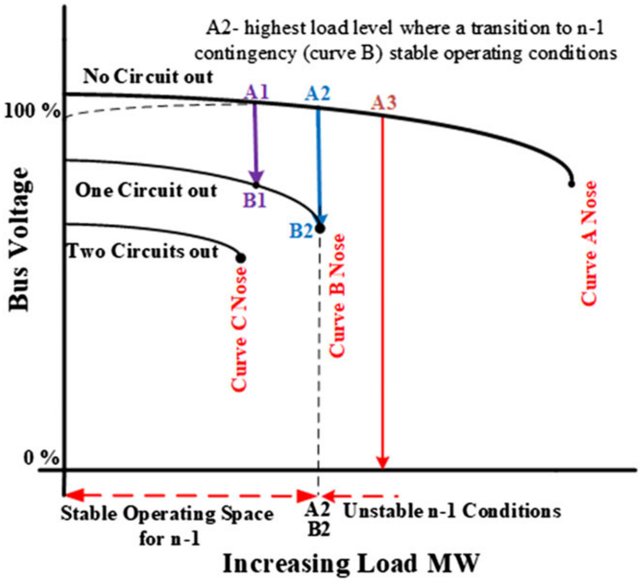

FIGURE 3 Voltage stability margins in contingency conditions[52]

3.1.1 | Short-term voltage stability

Short-term voltage stability refers to the dynamic nature of loads such as induction motor and another electronic load. The time-varying nature of the operating characteristics of load leads to a short-term voltage stability problem in the network. Short-time voltage stability can be studied by modeling the dynamics of loads. The study period of interest for short-term voltage stability is in seconds.

3.1.2 | Mid term voltage stability

The mid-term voltage stability problem arises when the short term period increases to minutes, ie, 2 minutes or more than that. It usually occurs because of activation of under load tap changers prior to the engagement of excitation limiters.

3.1.3 | Long-term voltage stability

Long-term voltage stability refers to the duration of several minutes. The outage of equipment results in voltage instability due to the loss of long-term equilibrium. Sometimes, slow acting equipment such as tap-changing transformers causes long-term voltage stability problems. Load shedding is the most appropriate solution in case of losing equipment from the network for a long time.

The following section expands the rules and regulations for designing UVLS schemes, which are helpful for power system operators, planners, and designers to design a reliable and efficient power system.

4 | APPLICATIONS OF UVLS SCHEMES

The Under Voltage Load Shedding Task Force (UVLSTF) of the Western Systems Coordinating Council (WSCC) established some regulations, which must be followed when designing a UVLS scheme. These regulations are given below.[38,53]

1. Protective devices and control schemes are usually incorporated in the load shedding scheme to prevent temporary voltage dips, ie, any low voltages that may be produced by installed air conditioners, sustained faults, and etc.
2. The typical time delay required to initiate load dropping varies between 3 to 10 seconds.
3. PTs connected above the set of automatic LTCs must be carrying UVLS relays.
4. The tripping signal for voltage pickup points must set higher fairly than the given “nose point” of the critical P-V or Q-V curve.

5. A well-checked and coordinated time delays of the adjacent systems, as well as the voltage pick-up points, is required so that UVLS does not trigger earlier.
6. To prevent false tripping and for increased reliability of operations, sufficient intelligence and redundancy should build inside the scheme.
7. To regulate the voltages to minimum operating levels, the loads should control in direct proportion while sustaining VAR boundaries as specified by WSCC's Voltage Stability Standards.

The typical phases chosen aimed at decentralized relay are:

1. Once monitored, bus voltages drop to 90% or lesser of standard, trip 5% of the load for a minimum of 3.5 seconds.
2. When bus voltages drop to 92% or lesser, trip 5% additional load for 5.0 seconds.
3. When bus voltages drop to 92% or lesser, trip 5% additional load for 8.0 seconds.

5 | INDUSTRIAL PRACTICES AND CLASSIFICATION OF UVLS SCHEMES

According to different protection schemes, the information of transmitting the tripping signal within a specified area can be categorized as follows:

5.1 | Centralized vs decentralized

In centralized[55] load shed arrangement, the tripping signal information is transmitted at numerous spots to under-voltage shed relays connected to main system buses within the critical part. These arrangements are termed as Special Protection Scheme[56] (SPS) and Wide Area Protection Scheme (WAPS).[57-61] With the recent developments in computer and network technology, the centralized UVLS has become feasible. On the other hand, the decentralized schemes[36] follow a similar principle to that of UFLS having its relay operate at the selected location when frequency/voltage drops below a threshold value.

5.2 | Static and dynamic

Fixed amount of load shed occurs in the static approach at every stage. However, dynamic approach depends on the type of disturbance and fluctuating performance of the system at each stage and it may change with time.

5.3 | Closed loop vs open loop

Closed-loop UVLS is intended to function for numerous periods, and every action depends on the calculated solution of an earlier action, or it may also consider working on system feedback. Whereas open loop emergency control action is based on offline simulations of postulated scenarios and does not readjust its action to ensure up to the system progress.

5.4 | Response based vs event based

Response-based scheme depends on the type of disturbance and magnitude of the voltage level. The low-level voltage magnitude affects the operation of the power system. Remedial action may be taken for these situations accordingly. Likewise, an event-based load-shedding scheme operates upon the identification of precise occasions.[62]

5.5 | Algorithmic decision based vs rule based

An algorithmic decision-based scheme is useful for long-term voltage instability while considering real-time applications. On the other hand, a rule-based approach depends on the initial conditions, such as load shedding, blocking transfer criteria, and probable events.

6 | PRINCIPLES OF UVLS

As debated by various investigators, three major UVLS concerns declared to be considered include the quantity, timing, and proper location of load shed.

6.1 | Amount of load shed

The amount of load shed must be optimized while triggering a load shedding event. An excessive amount of load shed creates a problem of over frequency and unnecessary customer interruption. On the other hand, shedding lesser load than required does not arrest voltage instability and may cause a voltage collapse. For deciding the fitness of an unstable power system, the load characteristics serve an important role. Typical loads include induction motors, thermostatically controlled loads (air conditioner or heater), discharge-type lamps, and underload tap changers (ULTC) which are dynamic and time varying in nature. Highly reactive loads are shed on a priority basis because they may create a deficiency of reactive power up to a dangerous level leading to voltage collapse. Usually, induction motors represent 20% of the load as recommended by the Western Electricity Coordinating Council (WECC),[63] so the contrivance of voltage uncertainty depends on the fraction of the motor load along with the nonmotor load.

The amount of load shed is optimized and may keep changing throughout the occurrence of a voltage collapse. The objective of UVLS techniques is to move a system towards stability while shedding the minimum possible load. A concrete approach in a previous study[64] offers the least amount and finest location of load to be shed. In this method, the issue of nonlinear optimization is resolved by means of a multistage approach, and the amount of load shed is minimized at each stage. Similarly, to estimate the amount of load shed, a technique based on genetic algorithm (GA) was utilized and implemented in the Hydro-Quebec system[65,66]; however, the approach is unable to grip a broader range of load behavior and a number of scenarios and is not suitable for short-term voltage instability problems. A model to minimize the amount of load shed using an incremental search for checking system behavior to restore time-domain simulations is given in the previous study.[65] The computing time is intensely reduced as for the concern of long-term voltage stability by using the Quasi-steady-state simulation technique by recognizing the weakest buses. Damped Newton-Raphson method was proposed in an existing study,[51] which uses modified power flow equations to estimate and minimize the amount of load shed by identifying the weakest bus of the system.

Meta-heuristic algorithms in a previous study[67] are proposed to achieve the least amount, correct location, and appropriate time of load shed, which include particle swarm optimization,[68] firefly algorithm,[69] evolutionary programming,[70] ant colony optimization,[71] artificial neural network,[72] genetic algorithm,[73] and quantum-inspired evolutionary programming.[74] To obtain feasible solutions while considering problem constraints, the use of evolutionary algorithms result in better accuracy and speed.

6.2 | Location for load shedding

The buses, which have a high influence on the voltage stability margins, are termed as a weak bus. Moreover, weak buses are usually located far away from generation, and there is no reactive source connected to these buses. In a power system, long-term planning, and operation studies, it is compulsory to recognize these buses. Thus, the remedial actions must be implemented in such a location. The most appropriate bus for shedding load is the one that has the highest value of dV/dQ (very fast decay of voltage), which designates further vulnerability to voltage collapse.[39] The best location of load shed, characterized in the arrangement of the weakest bus as presented in a previous study.[66] The authors of another study[75] rank the system buses and trigger UVLS on the weakest buses. However, this approach resulted in suboptimal load shed.

Using the multistage methodology inward nonlinear programming, a new multiport network is suggested for least amount of load shed at the appropriate location in an existing research.[64] The results achieved were matched and confirmed with the modal analysis approach. However, modal analysis cannot evaluate the maximum loading point and is unable to identify critical areas, and hence, areas were examined based on the base case.

Next section explains different type of popular indices used in the literature along with their mathematical expressions. These indices are very helpful in deciding the location of load shedding timely.

6.3 | Types of indices

In literature, different type of indices are utilized for optimization of power system operation and control. These indices are helpful to identify weak buses and best location for load shed. The different types of indices are utilized in the literature; some of them presented along with their mathematical formulation as follows.

6.3.1 | Voltage and line stability indices

Most of the line stability indices are expressed in terms of the power transmission concept of a single line model. Voltage collapse can be predicted based on the stability indices of lines. The objective of using the voltage/line stability index is to identify the collapse point in the interconnected complex power system.[76] These indices are used to access voltage/line stability of power systems. Voltage/line stability may be analyzed using different indices listed below; these indices derived for voltage stability analysis refer to either a bus or a line. The line stability index also indicates the stability of the connected bus (receiving bus) on that line. Although, the bus stability index indicates the stability of a particular bus. The power system operators may use these indices to recognize how close the system is to voltage collapse in a spontaneous way and respond accordingly. Note that a line may be connected to multiple buses; however, the load shed is performed on the bus, which has a high index value. The power system remains stable when all indices values remain less than one. However, an index value of one or higher indicates an unstable system. Some of the popular stability indices are as follows:

6.3.2 | Fast voltage stability index

The fast voltage stability index (FVSI) index is capable to identify the point of voltage collapse, critical areas, and maximum permissible load in a large power system. Moreover, it is also useful in determining the power system's maximum loadability, weak buses, and the most critical line in an interconnected system, which is useful for online voltage stability assessment. The recognition of critical buses by means of proximity indices is considered a substantial development. FVSI can be used to alarm a system operator before the power system reaches its bifurcation point.[77] An FVSI originating from the equation of two-bus network in Figure 4.

S_i, S_j = Apparent power on the sending and receiving end buses.
V_i,V_j = Voltage on sending and receiving end buses.
P_i, P_j = Active power on the sending and receiving end buses.
Q_i, Q_j = Reactive power on the sending and receiving end buses.

FVSI is formulated as

$$FVSI_{ij} = \frac{4{Z_{ij}}^2 Q_j}{{V_i}^2 X_{ij}}, \tag{1}$$

where X_{ij}, is line reactance between line *i* and *j*, Z_{ij} is the impedance between line *i* and *j*, Q_j is the reactive power flow at the receiving end, and V_i is the sending end voltage.

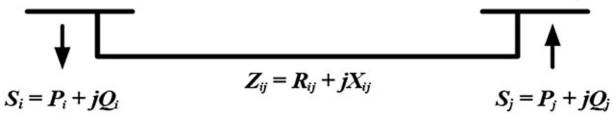

FIGURE 4 Model of two-bus power system

6.3.3 | Line stability index

Line stability index (LSI) is based on the power transmission concept in a single line. Figure 5 illustrates a single line of an interconnected network.

L_{mn} calls the stability index of that line; it is used to find the stability index for each line connected between two buses.[44] The line stability index for this model can be expressed as

$$L_{mn} = \frac{4XQ_j}{[V_i \sin(\theta - \delta)]^2}. \tag{2}$$

θ	line impedance angle
δ	the angle difference between the supply voltage and receiving end voltage
X	line reactance
Q_j	reactive power flow at the receiving bus
V_i	the voltage at sending end bus
R + jX	The impedance of the transmission line
P + jQ	Apparent power at receiving end

6.3.4 | Line stability factor (LQP)

line stability factor LQP as presented in.[78] The LQP is expressed as

$$\mathrm{LQP} = 4\left(\frac{X}{V_S}\right)\left(Q_r + \frac{P_S^2 X}{V_S^2}\right). \tag{3}$$

Equation 3 parameters are explained as

X	Reactance of transmission line
V_S	Sending end voltage
Q_r	Reactive power at receiving end
P_S	Active power at sending end

6.3.5 | Line voltage stability index

Line voltage stability index (LVSI) was proposed in a previous study[79] and considers the relationship between the bus voltage at the sending end of the reactive power lines.[80] It can be expressed as

$$\mathrm{LVSI} = \frac{4rP_r}{[V_S \cos(\theta - \delta)]^2} \leq 1. \tag{4}$$

6.3.6 | Stability index

This index refers to voltage stability for radial distribution networks as presented in another study.[81] Figure 6 demonstrates a two-bus distribution system and can be expressed as

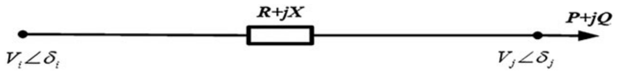

FIGURE 5 Model of the single line transmission

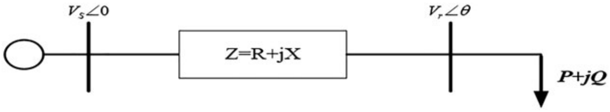

FIGURE 6 Model of two bus system

$$SI(r) = 2V_S^2V_r^2\text{-}V_r^4\text{-}2V_r^2(PR + QX)\text{-}|Z|^2\left(P^2 + Q^2\right). \tag{5}$$

$V_S \angle 0$	Sending end voltage angle 0
$V_r \angle \theta$	Receiving end voltage angle theta
$Z = R + jX$	Transmission line impedance
$P + jQ$	Apparent power at receiving end

6.3.7 | Voltage collapse prediction index

A voltage stability index based on the voltage phasor information of the participating buses in the system and the network admittance network called voltage collapse prediction index (VCPI) is proposed in another study.[82] VCPI is calculated by using the network admittance matrix and the measured voltage phasor at each bus. The technique can be implemented on any bus system. A mathematical model of VCPI is derived from the power flow equations solved by Newton Raphson method; hence, by equating the determinant of the matrix to zero, the index at bus j may be expressed as follows:

$$VCPI_k = \left| 1 - \frac{\sum_{m=1,\, m\neq k}^{N} V_m^*}{V_k} \right|, \tag{6}$$

$$\text{where,}\quad V_m^* = \frac{Y_{km}}{\sum_{j=1.j\neq k}^{N} Y_{kj}}. \tag{7}$$

V_k	Is the voltage phasor at bus k
V_m	Is the voltage phasor at bus m
Y_{km}	Is the admittance between bus k and m
Y_{kj}	Is the admittance between bus k and j
K	Is the monitoring bus
M	Is the other bus connected to bus k
N	Is the bus set of the system

The VCPI is calculated only with the information of phasor voltage of participating buses and impedance of related lines. This technique is fast enough for monitoring the power system online.

6.3.8 | Power transfer stability index

Kessel et al[83] derived the power transfer stability index (PTSI) by considering the two-bus Thevenin equivalent system, with the slack bus connected to a load bus by the single branch as shown in Figure 7.

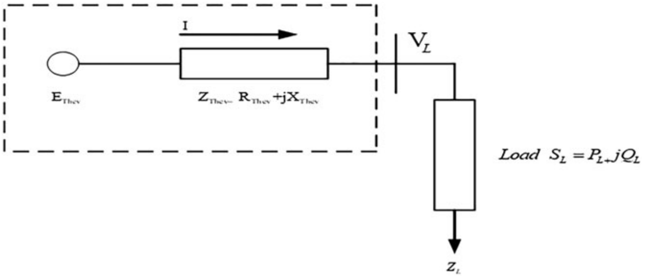

FIGURE 7 Model of Thevenin equivalent

The apparent power S_L magnitude can be calculated as shown in Equation 8.

$$S_L = \frac{E_{Thev}^2 Z_L}{Z_{Thev}^2 + Z_L^2 + 2Z_{Thev}Z_L\cos(\beta\text{-}\alpha)}. \tag{8}$$

Z_L	Load impedance
Z_{Thev}	Thevenin impedance
E_{Thev}	Thevenin voltage
α	Phase angle of the load impedance
β	Phase angle of Thevenin impedance

Further, the maximum load apparent power S_{Lmax} is then determined by differentiating ${}^{\partial}S_L/{}_{\partial}Z_L = 0$, which happens when $Z_L = Z_{Thev}$. Maximum load apparent power is given in Equation 9

$$S_{Lmax} = \frac{E_{Thev}^2}{2Z_{Thev}[1 + 2\cos(\beta\text{-}\alpha)]}. \tag{9}$$

Power transfer stability index is then defined by the ratio ${}^{S_L}/{}_{S_{Lmax}}$, which yields

$$PTSI = \frac{2S_L Z_{Thev}[1 + \cos(\beta\text{-}\alpha)]}{E_{Thev}^2}. \tag{10}$$

By using Equation 10, PTSI is measured at every bus Thevenin parameters can be tracked online based on phasor measurement unit (PMU) by recursive fewer means square algorithm.[84,85]

6.3.9 | New voltage stability index

A new voltage stability index (NVSI) proposed by other studies[86,87] originates from the two-bus network as shown in Figure 8. It gives the information of both active and reactive loading and neglects the transmission line resistance (Figure 8).

In general, the NVSI formulation can be expressed in terms of bus m and n as follows in Equation 11.

$$NVSI_{mn} = \frac{\sqrt[2X]{\left(P_n^2 + Q_n^2\right)}}{2Q_nX\text{-}V_m^2}. \tag{11}$$

The variables used in Equation 11 shows

Q_n	Reactive power at receiving end
P_n	Real power at receiving end
P_m	Real power at sending end
V_m	The voltage at sending end $\angle 0$

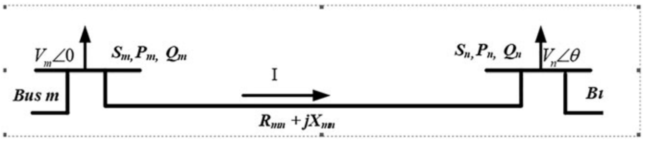

FIGURE 8 Model of two bus line

V_n	The voltage at receiving end ∠θ
X	The reactance of transmission line
θ	Line impedance angle
δ	Angle difference between sending end and receiving end voltage
$R_{mn} + jX_{mn}$	Transmission line impedance

Further expanding these indices,[88] the additional methods used to recognize weak parts of the power network. Earlier techniques include voltage stability limit,[89] Kohonen neural network-based approach,[90] singular value decomposition presented in another research,[91] and the voltage stability margin index employed by a previous study.[92]

6.4 | Timing of load shedding

Timing to operate a load-shedding scheme is critical for the correct operation of a power system. Operating a load shed scheme too early may cause unnecessary disturbance or alter initial operating conditions while operating it too late may not arrest voltage collapse. UVLS is operated when all reactive sources, control, and protection system are exhausted. Furthermore, the maximum time allowed before the UVLS scheme is activated is the time taken for all main system components to attempt system recovery.[39] The results of dynamic simulations to estimate the maximum time delay that a system can tolerate for load shedding are presented in previous studies.[63,93]

7 | VARIOUS LOAD-SHEDDING APPROACHES

Load-shedding techniques may be characterized as static or dynamic[94] based on the way they shed load. A fixed amount of load is shed by static schemes at each phase.[95] Dynamic approaches shed a variable quantity of load depending on the level of disturbance and dynamic response of the system at each phase[41,96] by modeling the elements of the network using algebraic and differential equations.[97] The behavior of a system under static or dynamic load shed is usually studied through time domain simulations.[98] This can accurately reflect the system dynamics of voltage instability, but the approach consumes a lot of computations time. Moreover, in-depth sensitivity information or the degree of voltage instability is not provided by this approach.[94]

Depending on the rate of change of voltage, the load can be shed either automatically or manually. If the voltage drop occurs in minutes, manual load shedding can be applied to stabilize the system, and if voltage decay is faster say in seconds then automatic load shedding is the most appropriate choice.[94] Three principal approaches of load shedding have been proposed so far.[31,99-101] The first approach is similar to under frequency load shedding, the load shed amount is considered as fixed by considering dynamic features of power systems and is determined using time simulation analysis presented in the previous studies.[18,32,75] These techniques are suitable for transient voltage instability. However, they are time consuming because of dynamic simulations. The second approach is built on the valuation of dynamic load constraints and its flaws; the result is impressionable to dynamic load model parameter. The third methodology employed the utilization of optimal power flow (OPF) equations of a power system's static model in the evaluation of the minimum load shed amount. Meanwhile, voltage stability dynamics are often slow; a static method would suggest a good approximation of system voltage stability.

Furthermore, the power system operation depends on the initial operating conditions, ie, before the occurrence of contingency and after contingency. For the secure and reliable operation of the power system, the mathematical models explain briefly the parameters, which affect the operation of the power system. Therefore, load shedding can be carried out, based on the mathematical equations given below.[31]

$$M\,\mathrm{in}\left[\sum_{i=1}^{N_K} Ci\left(\frac{\Delta P_{Di}}{\partial\lambda/\partial Pi}\right)\right], \tag{12}$$

$$P_{Gi}^{0} - P_{Di}^{0} + \Delta P_{Di} = \sum_{j=1}^{N} |V_i|\left|V_j\right|\left|Y_{ij}\right| \cos\left(\delta_{ij} + \delta_j - \delta_i\right), \tag{13}$$

$$Q_{Gi}^{0} - Q_{Di}^{0} + \Delta Q_{Di} = -\sum_{j=1}^{N} |V_i|\left|V_j\right|\left|Y_{ij}\right| \sin\left(\delta_{ij} + \delta_j - \delta_i\right), \tag{14}$$

$$(1+\lambda_{\min})\left(P_{Gi}^{0} - P_{Di}^{0} + \Delta P_{Di}\right) = \sum_{j=1}^{N} \cos\left|V_i^c\right|\left|V_j^c\right|\left|Y_{ij}\right| \cos\left(\delta_{ij} + \delta_j^c - \delta_i^c\right), \tag{15}$$

$$Q_{Gi}^{0} - (1+\lambda_{\min})\left(Q_{Di}^{0} - \Delta Q_{Di}\right) = -\sum_{j=1}^{N} \cos\left|V_i^c\right|\left|V_j^c\right|\left|Y_{ij}\right| \sin\left(\delta_{ij} + \delta_j^c - \delta_i^c\right), \tag{16}$$

$$V_i^{\min} \le V_i \le V_i^{\max},\ i\varepsilon \in N_L, \tag{17}$$

$$V_i^{c\text{-}\min} \le V_i^c \le V_i^{c\text{-}\max},\ i\varepsilon \in N_L, \tag{18}$$

$$\left|P_{ij}\right| \le P_{ij}^{\max},\ \forall ij \in \text{ Transmission lines}, \tag{19}$$

$$\left|P_{ij}^{c}\right| \le P_{ij}^{c\text{-}\max},\ \forall ij \in \text{ Transmission lines}, \tag{20}$$

$$Q_{Gi}^{\min} \le Q_{Gi}, \qquad Q_{Gi}^{c} \le Q_{Gi}^{\max}, \quad i \in N_G, \tag{21}$$

$$\Delta P_{Di}^{\min} \le \Delta P_{Di} \le \Delta P_{Di}^{\max}, \quad i \in N_D, \tag{22}$$

$$\frac{\Delta P_{Di}}{P_{Di}^{0}} = \frac{\Delta Q_{Di}}{Q_{Di}^{0}} \text{ Fixed power factor}, \tag{23}$$

$$P_{Gi}^{C} - P_{Di}^{C} + \Delta P_{Di} = \sum_{j=1}^{N} \left|{V_i}^{C}\right|\left|{V_j}^{C}\right|\left|Y_{ij}\right| \cos\left(\delta_{ij} + {\delta_j}^{C} - {\delta_i}^{C}\right), \tag{24}$$

$$Q_{Gi}^{C} - Q_{Di}^{C} + \Delta Q_{Di} = -\sum_{j=1}^{N} \left|{V_i}^{C}\right|\left|{V_j}^{C}\right|\left|Y_{ij}\right| \sin\left(\delta_{ij} + {\delta_j}^{C} - {\delta_i}^{C}\right). \tag{25}$$

These equations form the Newton-Raphson (N-R) power flow. The most significant feature of N-R is that it is more practical and efficient. Moreover, the number of iterations required to obtain a solution is independent of the system size. Additionally, N-R load flow converges fast as compare with other load flow methods. Equation 12 shows interruption cost by incorporating the sensitivity term ($\partial\lambda/\partial P$), which is usually the objective of load shedding. Equations 13 and 14 reveal initial operating conditions of a power system having index "0," where G_i and D_i account for generation and demand at bus i, respectively, whereas P and Q are related to active and reactive power. Moreover, ΔP_{Di} and ΔQ_{Di} are control variables, which show a change in active and reactive demands that helps to obtain optimal solution, Y_{ij} shows admittance of line i and j; δ_i, δ_j shows voltage angle at bus i and j, respectively; and δ_{ij} shows the difference of voltage angle at buses i and j. Index "c" in Equations 15 and 16 shows the of the power system in contingency or stressed condition along with minimum loading margin; ie, Equations 17 and 18 show the minimum and maximum voltage limits at bus *i* in normal and stressed conditions, respectively, where N_L displays a set of load buses. Transmission lines limits between bus *i* and *j* in normal and stressed condition relate to Equation 19 and 20. In Equations 21 and 22, reactive power and change in active power limits were shown; N_G shows a set of voltage controlled nodes, and N_D shows a set of demand/load buses. Equation 23 shows the ratio of control variables at fixed power factor. Finally, Equations 24 and 25 relate to dynamic stability constraints, which represent the variable after load shedding when contingencies occur.

Table A1 in the appendix describes the notations used in Equations 12 to 25.

The next section elaborates GA, PSO, hybrid optimization, and recent approaches used to solve the UVLS problem.

7.1 | Genetic algorithm applied in UVLS

A global optimization GA used to solve nonlinear, multiobjective problems; GA has gained substantial attention as a robust stochastic search algorithm. GA represents the symbol of biological natural evolution, and it applies the principle of "survival of the fittest" to continuously yield superior estimates to a solution. As a result, GA helps in the emergence of new, well-matched and better populations of individuals.[102] Three types of operators are included in the basic form of GA, namely, selection, crossover, and mutation.

GA and PSO were utilized to solve the problem of optimal load shedding in the IEEE 30-bus test system presented in a previous study.[37] By using the analytical hierarchy process (AHP), service interruption minimization and weighting factors were considered as a fitness function. The results showed that the minimum amount of load was shed by using GA, while faster convergence time achieved through PSO.

GA approach was utilized to investigate for optimal supply restoration, in distribution networks.[103] This technique was applied and verified on a realistic system of United Kingdom and was reported to be an optimized postfault supply restoration approach. However, the proposed technique was limited to distribution systems only.

A version of GA optimization was proposed in another study[104] for solving steady-state load-shedding problems. In this method, the objective function is to minimize the sum of squares of the difference between the connected active and reactive load. When examined on IEEE 14- and 30-bus test systems, assessed with the conventional approach,[105,106] the GA technique produced fewer loads to shed in strange events, and the results were further perfect in all situations. However, it suffers from a long convergence time not suitable for online applications. An improved GA-based centralized algorithm was proposed in a previous study[107] where the objective of stabilizing the system voltage of an optimization model was presented utilizing. The crossover and mutation rates were improved and thus, the convergence time of the algorithm. In IEEE 39-bus New England test system, the effectiveness of the algorithm was significant. Similarly, an optimization based GA tool was applied to estimate and perform automatic load shedding was presented in an existing research.[108] However, all these techniques are accurate but suffer from long convergence time due to use of GA.

7.2 | Particle swarm optimization applied in UVLS

Kennedy and Eberhart introduced PSO[109] in 1995. Inspired by social behavior of organisms such as fish schooling and bird flocking, this swarm intelligence technique was found to be fast and robust in resolving large-scale nonlinear multiobjective optimization issues. PSO remained broadly employed in numerous engineering problems including UVLS.

In a previous research,[100] the authors achieved optimal market-driven load shed and static voltage stability on modified IEEE 30-bus systems by using PSO and compared their technique with the locational marginal price (LMP). However, the proposed method is scalable to small power system only. A method to minimize the service interruption cost on its sensitivity and static stability margin values at the maximum loading point was proposed in another study.[101] Although, the proposed method was suffered from suboptimum load shed. General algebraic modeling system (GAMs) combined with the development atmosphere, nonlinear optimization, and evolutionary GA and PSO approaches; however, the outcomes of PSO remained better than from GAMs and GA methods.[99] The method was tested on the IEEE 14-bus system. PSO can effectively identify a global optimum solution in lesser time than mentioned methods above. While the minimum load shed was achieved through GA. However, the method was unable to shed optimum load.

7.3 | Hybrid optimization approaches for UVLS

Hybrid meta-heuristic algorithms are presented along with their merits and demerits in other studies.[110,111] Another study presents hybrid meta-heuristic techniques application for optimal load shedding planning and operation in an islanded distribution network integrated with distributed generation.[112] To solve the UVLS problem a hybrid PSO and simulated annealing (SA) method were presented in a previous study.[113] A more efficient way of load shedding is achieved by utilizing the strong point of SA in PSO. For long-term voltage stability, the proposed technique achieved optimal under-voltage load shedding. On the basis of the technical and economic priority of loads, an optimal UVLS scheme is generated, which is capable of maintaining predefined voltage stability. The proposed technique works satisfactorily on the IEEE 14- and 118-bus test systems. Each test shows the superiority of the hybrid method for finding the amount of load shed and recognition of a global optimum solution in minimum runs and thus, has high global convergence. However, the proposed technique was limited to long-term voltage stability only. A UVLS considering dynamic security by the use of PSO reported in a previous study[114] developed model intended to stipulate for postcontingency circumstances and achieved suitable voltage stability margin by disrupting a fraction of loads at least cost. However, the amount of load shed was not optimum.

A hybrid technique that combines linear programming (LP) and PSO was developed.[115] The proposed method removes a transmission line overloadings in contingency conditions and resolves the issues of low convergence speeds. The proposed hybrid technique was employed successfully on the IEEE 14-bus system by considering two critical contingencies. Finally, the proposed hybrid based algorithm is fast and accurate. However, it was observed that LP was unable to solve nonlinear problems, and the method is scalable to small power system only.

Optimal load shedding and enhanced voltage stability were achieved by the combination of modal analysis and PSO technique.[116] Best tap setting of the transformer in the initial stage prevention control is used with the help of PSO optimization and achieved the best possible voltage stability margin. For the annual peak load in the year 2009, the proposed hybrid technique was successfully deployed on the Iranian transmission network areas. The proposed technique followed the little amount of load shed with substantial enhancement in average voltage profile and voltage stability margin of the system. However, the proposed technique was applicable to a particular transmission network only and having long convergence time as well.

A comprehensive learning particle swarm optimization (CLPSO) has been proposed in a previous study[117]; the power balance is achieved with the help of load shedding in each island. The proposed approach was tested on two test system, a meshed network 66 kV, 45-bus Egyptian, and 33-radial bus system. However, the proposed method is limited to distribution systems only. A hybrid technique in which firefly and PSO are combined to achieve minimum load shed and correct location for load shed was proposed and tested on IEEE 30-bus test system.[118] However, the technique was suffered from suboptimal load shed. In another study, a new integer value modeling of optimal load shedding to prevent voltage instability was achieved through hybrid discrete particle swarm optimization by considering multiple objectives.[119] The proposed methodology was implemented on the IEEE 14 and 30 bus test systems. Although the load shed by proposed technique was not optimum and not scalable to large power systems. A robust UVLS scheme to improve transmission line performance considering minimum active power loss, the maximum voltage stability and minimum customer interruption cost were modeled as a quadratic function by combining GA and PSO in a previous study.[120] However, the proposed technique was unable to shed optimum load.

7.4 | Recent approaches for UVLS

Probabilistic undervoltage load shedding using point estimate method was presented in a previous study.[121] The drawback was long simulations time, so not fit for real-time applications. Techno-economic impacts of automatic undervoltage load shedding under emergency condition showed that automatic UVLS is superior to manual UVLS.[122] However, the proposed technique is applicable to the Austrian grid only having very long simulation time suitable for offline applications only. A new undervoltage load shedding method to reduce active power curtailment presented in a previous study.[123]

Some other approaches include minimal load shedding using swing equation,[124] an improved load shedding scheme by considering distributed generations,[125] intelligent load shedding based on active participation of smart appliances,[126] and an analytical adaptive load shedding scheme against severe combinational disturbances proposed by an existing study.[127] A swarm optimization technique for optimal load shedding under the presence of FACTS devices by making

TABLE 2 Summary of past contributions

S.NO	Technique/ Test System	Reference	Other Techniques for Comparison	Achievements/ Contributions	Limitations
1	Genetic algorithm (GA)/ practical UK system	Luan et al[103] (2002)	None	A technique for supply restoration in distribution networks optimal load shedding	Applicable to the particular distribution system only.
2	GA/IEEE 14-bus test system and IEEE 30-bus test system	Al-Hasawi and El Naggar[104]	The load flow equations	Optimal load shed for abnormal conditions	Long convergence time
3	Particle swarm optimization (PSO)/ IEEE 14- and 118-bus test systems	Amraee et al[101]	GA	Identification of collapse point Minimum service interruption cost Consideration of technical and economic aspects of each static load	Dynamics nature loads were not considered.
4	GA and PSO applied individually/IEEE 30 bus test system	Rad and Abedi[130]	PSO	Minimizes the amount of load shed using GA Faster convergence time achieved through PSO	Not scalable to large and complex power systems. Voltage stability not achieved.
5	HPSO-SA/IEEE 14 and 118 bus test systems	Sadati, et al[99]	PSO-based simulated annealing (PSO-SA)	Optimal load shed using PSO-SA Static voltage stability margin and its sensitivity at maximum loading point	Slow convergence rate, not suitable for transient conditions
6	Hybrid modal analysis and PSO/Gharb and Bakhtar areas of Iranian transmission network	Jalilzadeh, et al[116]	PSO and modal analysis	Achieves best transformer tap setting and voltage stability margin The optimal amount of load shed at the best location	Designed for a particular transmission network and unable to identify critical areas or maximum loading point
7	HPSO-LP linear programming/IEEE 14 bus test system	Hagh and Galvani[115]	linear programming (LP) and PSO	Fast convergence Elimination of transmission line overloading	Not scalable to large power and complex systems.
8	GA/500 kV power system Uruguay	Guichon et al[108]	None	Achieve optimal load shed through an automatic process	Limited to direct current (DC) load flow only.
9	PSO/IEEE three-bus and modified 30-bus test systems	Hosseini-Bioki et al[100]	Locational marginal price (LMP)	Greater voltage stability margin achieved through social welfare	For large power and complex systems, the proposed technique was not scalable
10	Hybrid discrete PSO/ IEEE 14- and 30-bus test systems	Ahmadi Alinejad[119]	PSO	A new method for voltage stability using integer-value modeling	Suboptimal load shed
11	HGAPSO/IEEE 57-bus test system	M. Ojaghi[129]	PSO	Minimum customer interruption cost	Unable to shed optimum load,

(Continues)

TABLE 2 (Continued)

S.NO	Technique/ Test System	Reference	Other Techniques for Comparison	Achievements/ Contributions	Limitations
				Minimum active power loss Elimination of transmission line under overloading	voltage stability not achieved
12	Firefly algorithm and PSO/IEEE 30-bus test system	Sonar and Mehta[118]	Firefly and PSO	Firefly converged faster than PSO	Amount of load shed was not optimum
13	Techno-economic impacts/European transmission systems	Estebsari et al[122]	Manual and automatic under voltage load shedding (UVLS)	Comparison of automatic and manual UVLS schemes showed that automatic UVLS is superior	Short-term voltage stability ignored while has slow convergence. Designed and tested on a particular Austrian grid.
14	Probabilistic UVLS point estimate method/IEEE 14- and 118-bus test systems	Kaffashan and Amraee[121]	Monte Carlo simulations	An accurate UVLS scheme using the point estimate method with a less computational complexity	Long convergence time, not suitable for real-time applications.
15	Hybrid GA and neural network/IEEE six- and 14-bus test systems	Tamilselvan and Jayabarathi[149]	GA and NN	Minimum load shed with fewer deviations in voltage	Slow convergence rate and not scalable to large and complex power systems

TABLE 3 Conventional and computational techniques

No	Features	Conventional Technique	Computational Techniques
1	Optimum load shedding	Unable to offer optimum load shedding	Capable to shed load, which are optimum
2	Complex and large power system	Unable to grip proficiently with large and complex power systems	Handle powerfully with all size and complex type of power system

a comparison based on computation.[128] Application of load shedding schemes for distribution network connected with distributed generation presented in another study.[129] However, all these techniques either suffer from suboptimal load shed or long convergence time. Every optimization technique has their own limitations as given in Table 4, so it can be concluded that hybrid optimization techniques may overcome these limitations by combining their strengths, which results in more accurate and optimal solutions to practical engineering problems. Therefore, researchers are adopting hybrid techniques to solve nonlinear and mutiobjective optimization problems. Moreover, an improved algorithm for optimal load shedding with voltage stability as constraint presented in a previous study.[147]

Unlike traditional power systems, contemporary power systems can no longer solely depend on fossil fuels for power generation owing to the economic and environmental constraints. Therefore, the penetration of renewable energy sources for power generation has increased rapidly. Moreover, distributed generations have also been used to improve the reliability of existing power systems by integrating them together. However, this has resulted in increased complexity of the power networks and given rise to voltage stability issues related to islanding operation. These problems dictate for the need to design new techniques for UVLS, which are fast enough to operate and recover the power system from contingency in real time.

Several meta-heuristic techniques to optimize load shedding in the minimum possible time while satisfying all the power system constraints have been proposed in the literature.[148] A new voltage stability index for online monitoring and load shedding is proposed in another study.[87] Similarly, the authors of previous research[76] propose a technique to identify the critical lines in a power system for optimal load shedding. A new strategy for optimal load shedding incorporating the power tracing index is proposed in an existing research.[88] In another work,[80] a supervised learning based technique to predict the line voltage stability index is proposed.

Table 2 summarizes past contributions.

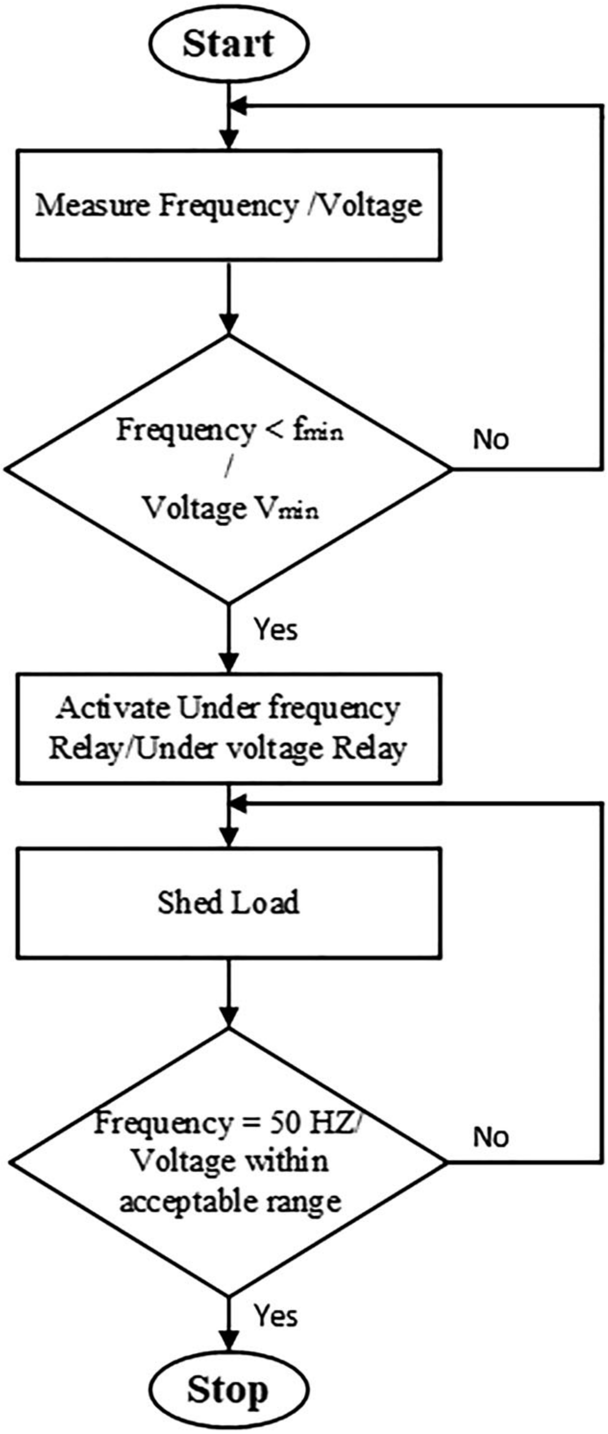

FIGURE 9 Conventional load shedding techniques flowchart[98,151]

TABLE 4 Benefits and disadvantages of computational techniques

Reference	Technique	Advantages	Disadvantages
73,103,130-133	Genetic algorithm (GA)	Using GA, the amount of load shed is minimum; it is also helpful in resolving nonlinear multiobjective problems. GA is termed as a global optimization technique with a high degree of accuracy.	The response of GA is slow, which is unsuitable for online applications.
68,99-101,130,134	Particle swarm optimization (PSO)	PSO is best suited to find optimum value and it takes minimum time to reach the optimal solution.	PSO is effortlessly stopped by partial optimization.
72,135	Fuzzy logic control (FLC)	FLC may be utilized on large power systems.	FLC require prior information for membership parameters.
136,137	Big bang big crunch (BB-BC)	BB-BC has the ability to solve problems that depend on a large number of variables.	It is a nature-inspired algorithm.
71	Ant colony optimization (ACO)	ACO can be used in dynamic applications, its convergence is guaranteed.	Time of convergence is uncertain, very complicated coding.
70,138,139	Artificial neural network (ANN)	ANN is best suited to ensure an optimum amount of load shed.	Satisfactory results can be obtained by ANN for known cases but cannot provide accurate results for unknown cases.
74,140	Quantum-inspired evolutionary programming (QIEP)	QIEP best handle the multi-objective problems and very well suited for multiple scenarios.	Since its operation depends on bit by bit so may be unsuitable for online application because of slow speed.
72,141,142	Adaptive neuro-fuzzy interference system (ANFIS)	Combine both features of ANN and FLC and give best-optimized results.	It is limited to Sugeno-type systems only.
143-146	Firefly algorithm (FA)	Advantages of FA over other algorithms: automatically subdivision and the ability to deal with multimodality. Also, FA gives more precise, robust, easy, and parallel implementation.	It has slow convergence speed, getting trapped into local optima and no memorizing capability.

8 | CONVENTIONAL AND COMPUTATIONAL LOAD SHEDDING TECHNIQUES

Conventional methods are not suitable for resolving nonlinear and multiobjective problems in large and complex power systems with the preferred precision and speed. These techniques result in an increased blackout owing to insufficient or excess load shed.[150] Consequently, computational intelligence techniques remain the best choice for estimating optimal load shed. Under frequency and UVLS techniques is shown in Figure 9. The increase in the complexity of the present day power systems has necessitated the use of computational intelligence techniques (CIT) due to their scalability, accuracy, and robustness in handling complex systems.[39,150]

Various CITs have been proposed. Table 3 compares the salient characteristics of conventional and computational techniques, while Table 4 summarizes the benefits and drawbacks of computational techniques.

9 | CONCLUSION

This article critically reviewed various UVLS schemes focusing on the key disputes such as amount, time, and location of load shed. It also provided a one-stop review of the techniques and policies for UVLS. Conventional UVLS techniques are no longer fit for modern and complex power systems. The introduction of computational intelligence techniques in UVLS schemes is capable to improve the reliability and robustness of power systems by reducing the number of blackouts. In addition, the voltage and line stability indices along with their mathematical models and different industrial practices being executed by power industries are also reviewed. Computational intelligence techniques in load shedding are discussed with their pros and cons. Hybrid approaches have shown promise in terms of obtaining optimal solutions to practical problems. However new techniques can be developed through analysis and advanced simulations of existing techniques making them suitable for actual applications in modern power systems.

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APPENDIX A

TABLE A1 Notations used in mathematical equations

P_{Gi}^{0}	Active power generation at bus *i* at initial operating condition (MW)
P_{Di}^{0}	Active power demand at bus *i* at initial operating condition (MW)
P_{Gi}^{c}	Active power generation at bus *i* in contingency state (MW)
P_{Di}^{c}	Active power demand at bus *i* in contingency state (MW)
ΔP_{Di}	Change in active power demand (MW) at the initial operating condition
Q_{Gi}^{0}	Reactive power generation at bus *i* at initial operating condition (MVAr)
Q_{Di}^{0}	Reactive power demand at bus *i* at initial operating condition (MVAr)
ΔQ_{Di}	Change in reactive power demand (MVAr) at the initial operating condition
Y_{ij}	Admittance of line *ij* (1/Ω) at the initial operating condition
θ_{ij}	Admittance angle of line *ij* at the initial operating condition
δ_i	Voltage angle at bus *i* at the initial operating condition
δ_i^c	Voltage angle at bus *i* in a contingency state
δ_j	Voltage angle at bus *j* at the initial operating condition
δ_j^c	Voltage angle at bus *j* in a contingency state
δ_{ij}	Voltage angle at line *ij* at initial operating condition
$\lambda_{\min}$	Minimum loading margin
V_i	Bus voltage at the initial operating condition at bus *i* (V)
V_i^c	Bus voltage in contingency state at bus *i* (V)
V_j	Bus voltage at the initial operating condition at bus *j* (V)
V_j^c	Bus voltage in contingency state at bus *j* (V)
$V_i^{\min}$	The lower limit of the voltage at initial operating condition bus *i* (V)
$V_i^{\max}$	The higher limit of the voltage at initial operating condition bus *i* (V)
$V_i^{c-\min}$	The lower limit of the voltage at bus *i* in contingency state (V)
$V_i^{c-\max}$	The higher limit of the voltage at bus *i* in contingency state (V)
P_{ij}	Active power flow line *ij* at initial operating condition (MW)
$P_{ij}^{\max}$	The higher limit of active power flow line *ij* at initial operating condition (MW)
P_{ij}^{c}	Active power flow line *ij* in contingency state (MW)
$P_{ij}^{c-\max}$	The higher limit of active power flow line *ij* in contingency state (MW)
N_D	Set of load/demand buses
N_G	Set of generation buses
N_L	Number of lines